Alfvén Waves, Alpha Particles, and Pickup Ions in the Solar Wind

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Abstract. Past studies of the properties of Alfvén waves in the solar wind have indicated that (1) the amplitude of the velocity fluctuations is almost always smaller than expected on the basis of the amplitude of the field fluctuations, even when the anisotropy of the plasma is taken into account, and (2) the alpha particles often do not participate in the wave motions because (hey "surf" on the waves carried by the proton fluid. Ulysses data are used to demonstrate that (1) the discrepancy between the velocity and field fluctuations is greater at high heliographic latitudes than in the ecliptic plane, and (2) the alphas do participate in the waves, being either in phase or out of phase with the proton motions depending on whether the differential flow speed between the alphas and protons is greater than or less than the "observed" wave speed, $V_{wave} = \delta V B_o/\delta B$, as determined from the ratio of amplitudes of velocity and magnetic fluctuations. Tbc possibility that the modification of Alfvén wave propagation speed is due to pressure anisotropies resulting from pickup ion distributions is investigated.

introduction

At low frequencies, the properties of transverse magnetohydrodynamic (MHD) waves, called Alfvén waves, arc expected to satisfy the relation (velocities below in the fluid (zero total momentum) frame:

$$\delta V_i = -(\frac{\omega}{k} - V_{i\parallel})\frac{\delta B}{B_o} \qquad (1)$$

where $V_{i\parallel}$ is the velocity of ion species i in the fluid frame (zero total momentum), **B** is the vector magnetic field, B_o is the field magnitude, VA is the Alfvén speed

$$V_A = W(4\pi\rho)^{1/2} \qquad (2)$$

p is the plasma density, and A is a factor that takes account of any anisotropy in the plasma.

$$V_{wave} = \pm\frac{\omega}{k} = V_A A, \; A^2 = 1 - 4\pi(p_\parallel - p_\perp)/B^2 \qquad (3a,b)$$

where $p_\parallel$ and $p_\perp$ arc the total plasma pressures parallel and perpendicular to the magnetic field, and V_{wave} is the wave speed. Note that relative streaming between protons and alpha particles contributes to parallel pressure (*Neugebauer et al.,* 1984). The p in the above equations refer to the density of the total fluid. If the principal ions arc protons and alpha particles, then, the fluid velocity in the spacecraft frame is,

$$\mathbf{V} = \frac{n_p V_p + 4 n_\alpha V_\alpha}{n_p + 4 n_\alpha} \qquad 4)$$

where the n's refer to number densities and the subscripts $_p$ and $_\alpha$ refer to protons and alphas respectively. Since ~95% of the ions in the solar wind are protons, it is often assumed that the fluid frame is the same as the proton frame; this study does not make that assumption.

Through the comparison of proton velocities with magnetic field vectors measured on Mariner 5, *Belcher and Davis* (1971) showed that large-amplitude waves were often detected propagating outward from the Sun, with the purest modes found in high-speed streams and on their trailing edges. They also found that $V_{wave} \approx 0.78$ VA, and suggested that the anisotropy required to give A = 0.78 seemed reasonable. In a later paper, *Belcher and Solodyna (1975)* derived a value of A = 0.68, and commented that the reason for such a "discrepancy" between the observed and the expected value of A ≈ 1.0 was not understood. Similar problems were found with the jump conditions across rotational discontinuities (*Belcher and Solodyna*, 1975; *Neugebauer et al., 1984),* which can be thought of as steepened Alfvén waves. Using ISEE-3 data, *Neugebauer et al. (* 1984) obtained a discrepancy of a factor of 0.77 even after including the observed pressure anisotropies associated with double-peaked proton distributions, anisotropic alpha-particle distributions moving faster along the field than the protons, and electrons. Another noteworthy feature of Alfvén waves in the solar wind is their effect on the alpha-particle component of the plasma. The data acquired by the Helios spacecraft in the high-speed wind from coronal holes clearly showed large-amplitude fluctuations of the direction of the proton velocity vector which were closely correlated with fluctuations in the field direction; at the same time the flow direction of the alpha particles remained nearly radially outward (*Marsch e/ al.,* 1982). At the smaller heliocentric distances sampled by Helios (from 1.0 to 0.3 AU), the alpha-particle velocity exceeded the proton velocity by an amount that approached or nearly equaled the Alfvén speed VA. *Marsch et al.* concluded that the alphas move through the proton fluid at approximately the same speed as the waves, and so do not feel the wave motion.

In this paper, Ulysses data arc used to test consistency with the relations summarized in Equations (1)–(5) above and to examine the relation between the alpha particles and the waves under a wide range of solar wind conditions. We find the observed wave speed estimated from $V_{wave} = \delta V B_o/\delta B$ to be less than that calculated from eqs. 1-5. The possibility that anisotropic pickup ion distributions may explain the discrepancy is investigated, and other alternatives arc discussed.

Proton and Alpha Velocity Fluctuations

The data used in this study were obtained by the Ulysses spacecraft during both its in-ecliptic flight to Jupiter and its out-o!-the-ecliptic trajectory through the end of 1994. During that time Ulysses covered a heliocentric distance range of 1.5 to 5.4 ALJ and a latitude range of -O to -80°. The plasma data were obtained by the Ulysses solar wind plasma experiment named Solar Wind Observations Over the Pole.s of the Sun (SWOOPS). The design and operation of SWOOPS arc described by *Bame et al.* (1 992). In its usual mode of operation, SWOOPS measures the three-dimensional distribution of protons and alphas with spacings of 5% in energy, ~5° in both polar and azimuthal angles, and either 4 or 8 minutes in time, depending on whether the spacecraft is being [racked or is storing data for later readout. SWOOPS obtains electron distributions every 3.1 or 6.3 minutes, and the electron data have been interpolated to match the times of ion observations. The magnetic field data were obtained by the Ulysses magnetometer for which A. Balogh is the principal investigator (*Baloghetal.*, 1992).

I'here were many periods when hrr,ge-amplitude Alfvén waves were clearly present in the Ulysses data, especially when the spacecraft was in the high-speed stream from the southern polar coronal hole (e. g., *Smith et al.*, 1995). Figures 1 and 2 display scatter diagram of the north-south (N) components of the proton and alpha-particle velocities plotted versus the N component of the magnetic field normalized by the field magnitude for two different 12-hour intervals. The N component was selected for study because the motions in that direction are less affected by stream-stream interactions than arc the radial (R) or tangential (T) components.

Consider first the data shown in Figure 1, obtained near the ecliptic when the spacecraft was 5.22 AU from the Sun (1992, Jan. 17, 12:00-24:00). The N components of both the proton and alpha-particle velocities were positively correlated with B_N/B (correlation coefficients of 0.88 and 0,90, respectively) as would be expected for Alfvén waves traveling away from the Sun when the interplanetary magnetic field points toward the Sun (B_R < O). The average Al fvén speed during this interval was 34.5 km/s, while the anisotropy factor calculated from the observed proton, alpha, and electron distributions (including all anisotropies and differential streaming) was A_{calc} = 0.92, corresponding to an expected wave speed of 31.7 km/s. When the N component of the fluid velocity V_N is compared to B_N/B, the slope of the scatter diagram (not shown) yields an effective wave speed of only 20.5 km/s, so that A_{obs} = 0.59, which is considerably less than A_{calc} = 0.92. The alplu-particle streaming velocity relative to the proton fluid ($V_{\alpha p}$ = 5.5 km/s) was much less than the wave velocity (20.5 km/s) so the alpha particles participated in the wave motion.

The alpha-particle behavior in the waves observed in the high-latitude coronal hole data shown in Figure 2 is remarkably different. The value of A calculated from the ion and electron distributions was A_{calc} = 0.91, while the effective wave speed calculated from the fluid V_N versus B_N/B scatter diagrams was only 19.] km/s, corresponding to A_{obs} = 0.43. The alphas were streaming through the proton fluid with a speed of 33.8 km/s, which exceeded the observed V_{wave} = 19.1 km/s. Because tbc alphas were traveling faster than the wave speed, the wave appeared to the alphas to be traveling opposite to the apparent wave direction seen by the protons, and so motions of the alphas and protons were out of phase with cacb otbcr, which explains the negative slope for the alphas on tbc right side of Figure 2.

The two illustrative intervals shown in Figures 1 and 2 were typical of the two cases $V_{\alpha p} > V_{wave}$ and $V_{\alpha p} < V_{wave}$. Figure 3 demonstrates the relation between proton and alpha motions over a wide range of solar wind conditions. Each point in that Figure was calculated for a 6-hour interval which was judged to have significant Alfvén wave activity by satisfying the criteria that (1) the absolute value of tbc correlation coefficient between the N components of the proton velocity V_{pN} and the field B_N was greater than 0.80, and (2) the root mean square magnetic field magnitude fluctuation was less than 10% of the field magnitude. The data used for this survey included all the data taken in the flow from the south polar coronal hole through Dec. 31, 1994, together with periods identified as "norI-interaction regions" prior to the spacecraft entry into the coronal hole flow. For each of the resulting Alfvénic intervals, Figure 3 shows the correlation between the N components of tbc alpha-particle velocity and the magnetic field plotted versus the ratio of the alpha-particle proton differential field-aligned velocity, $V_{\alpha p}$, to the "observed" wave speed calculated from the slope of a Icast-squares fit of the fluid velocity V_N versus B_N/B. The sign for the ordinate was chosen to be positive if V_{pN} and $V_{\alpha N}$ were in phase and negative if tbcy were out of phase. The plot in Figure 2 shows that the sign of the correlation between V_{pN} and $V_{\alpha N}$ dots indeed depend on whether the speed of the alpha-particle streaming relative to the protons is greater than or less than V_{wave}. For completeness, it is noted that there were a few periods with $V_{\alpha p}/(V_{wave}) > 2$ which were not included in the plot; for each of those intervals, V_{pN} and $V_{\alpha N}$ were anticorrelated, as expected.

The behavior of the alpha particles relative to the protons gives us confidence that the wave speeds obtained from the slopes of the V_N-B_N/B scatter diagrams are roughly correct and that the discrepancy between A_{calc} and A_{obs} is not caused by some gross error in the measurements or instrument calibration. Figure 4 shows the size of the discrepancy for Alfvénic intervals averaged over 10° in latitude (except for the closest interval, which was averaged over only 5°) as a function of heliocentric distance. The triangles in the plot show the value of A_{obs}^2 corresponding to the slope of the V_N-B_N/B correlations while the crosses show A_{calc}^2. The error bars denote the standard deviations about the mean.

Two possible explanations of the discrepancy between A_{calc} and A_{obs} are that: (1) the waves arc not, in fact, Alfvén waves, or (2) the missing anisotropy is contributed by some ion population not included in the estimation of A_{calc}. Since the same discrepancy in propagation velocity is seen at rotational discontinuities (*Belcher and Solodyna*, 1975; *Neugebauer et al.*, 1984), wc believe tbc second explanation is probably tbc correct one.

Anisotropic Pickup Ions or Other Cause?

This section presents a model based on the hypothesis that the missing anisotropy arises from interstellar pickup ions, and discusses alternative explanations. *Gloeckler et al.* (1993) have reported pickup H^+ and He^+ number densities of 5.4x 10-S and 6.7×10^{-5} cm^{-3} at 4.82 AU in the ecliptic; for a thermal speed of 700 km/sec (fast solar wind), the associated pressure is 1.5x10-12 dyne/cm^2 while $B^2/4\pi$ is about 4×10^{-12} dyne/cm^2. Pickup ions are initially created traveling inward along the magnetic field in the solar wind frame, and if the inward velocity is greater than tbc perpendicular thermal speed, then $p_\| > p_\perp$ and the wave speed is reduced. For the parameters just mentioned, the pickup ion distribution, if very anisotropic, could modestly affect the wave speed.

At bighcr latitudes, the B_T component and magnitude of the magnetic field arc decreased and greater modification of wave properties seems possible. In addition to the streaming of tbc pickup ions along the large scale spiral magnetic field, smaller scale effects may also occur. For example, *Gloeckler et al.* (1994) have observed correlated variations in the densities of pickup protons and helium ions, and attributed this to streaming into local magnetic traps. Such streaming would also produce pressure anisotropies.

The model used here to obtain an upper limit for the possible effects of the large scale spiral field on pickup ions corresponds to the case of no scattering of pickup ions by interplanetary waves and no streaming into magnetic traps. It is generally assumed that waves generated by the initial distribution of pickup ions rapidly pitch-angle scatter the ions into an approximately spherical shell in velocity space (*Lee and Ip*, 1987), but the expected waves from this process are rarely observed. We assume instead that pickup ions are not scattered by electromagnetic waves as they stream adiabatically in the large scale heliospheric field; this allows an upper limit for the modification of wave properties to be obtained. The cold interstellar neutral gas model of *Thomas* (1978) is used together with the parameters for the neutral distribution used by *Gloeckler et al.* (1 993). Although we use the same neutral model as *Gloeckler et al.*, our pickup ion densities are larger due to the lower radial velocities of outward traveling ions (which are at pitch angles where they might not typically be observed). The collations of adiabatic particle motion (i.e., gyro-averaged drift equations) in the strong electric field case (electric field drift ≥ thermal speed) are obtained from *Sivukhin* (1965). A Parker spiral interplanetary magnetic field is assumed with B_R independent of latitude and longitude and equal 10 3.5 nT at 1 AU. The solar wind is assumed to be radial with V = 750 km/see at latitudes > 35°, 400 km/sec at 0° latitude, and to vary as half of a cosine wave between latitudes of 0° to 35° Calculations were done along the orbital track of Ulysses at 10° latitude intervals taking both the heliocentric distance and longitude with respect to the flow direction of the interstellar gas into account. Figure 5 compares the change in A* required to explain the observation (i.e., $A_{calc}^2 - A_{obs}^2$) to the anisotropy ratio due to streaming pickup ions as computed from the model (i.e., $1 - A_{pu}^2 = 4\pi(p_{pu\parallel} - p_{pu\perp})/B^2$ where the subscript pu denotes the contribution of pickup ions). Between about 2 and 4 AU (when Ulysses was poleward of -40° latitude), the model value of $1- A_{pu}^2$ is more than sufficient to account for the discrepancy between A_{calc} and A_{obs}. Over most of that region, however, $1 - A_{pu}^2 > 1$, which implies that A_{pu} is imaginary and that the plasma is firehose unstable; if for some reason resonant instabilities did not start to scatter the ions, then the firehose instability would, Inside 2 AU (equatorward of -70°) and between 4 (- -45°) and -S AU (-25”), the model predicts that the effect of pickup-ion anisotropy is somewhat less than needed to explain the observed wave speeds. Beyond 5 AU, the model gives $A_{pu}^2 > 1$, which suggests that heavy ion anisotropies may contribute to the mirror instability and the production of magnetic holes. In addition to the anisotropies computed from the model, there may be further contributions from the streaming mechanism discussed by *Gloeckler et al.* (1994).

The model was also run for the ecliptic at 1 AU. For a solar wind speed of 400 km/s, $1 - A_{pu}^2$ varied from *0.01* to 0.02 over the course of a year. For a speed of 750 kinds, $1 - A_{pu}^2$ ran from 0.08 to 0.21. Not surprisingly, the effect is very dependent upon solar wind speed. Since most studies of Alfvén waves near 1 AU have typically dealt with high speed streams, the effect of pickup ions on the wave speeds observed there may have been significant.

An alternative point of view is that the reduction in the Alfvén ratio (r_A, kinetic energy of fluctuations to magnetic energy) is due to solar wind turbulence effects (e.g., *Roberts et al.*, 1992), although generally (but not always) such theory would predict r_A to be about one ($r_A=1$ is equivalent to $A^2_{obs}=1$). Our opinion is that such effects could not account for the reduced wave speeds observed at rotational discontinuities (*Belcher and Solodyna, 1975; Neugebauer et al., 1984).* On the other hand, it is clear that the magnitude of the reduction we calculate in the ecliptic at 1 AU (last paragraph) is marginal even assuming solar wind speeds of 750 km/sec and no scattering of pickup ions. It may be that in differing circumstances (high speed versus low speed solar wind, Alfvénic versus non-Alfvénic) more than one process is important in determining r_A. In particular, the effect of pickup ions would be greatest at high latitudes beyond 1 AU, where large negative values of $1 - A_{pu}^2$ are calculated and where the greatest reduction in wave speed is observed. Further work to characterize the effect at 1 AU as a function of angle with respect to the flow of the Local inter-Stellar Medium should definitively test whether pickup ions make a significant contribution to the speed reduction.

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Figure Captions

Figure 1. The relation between V_N and B_N for protons (left panel) and alpha particles (right panel) for a 12 hour interval near the ecliptic during which Alfvén waves were present.

Figure 2. Same as Figure 1 but for high latitudes.

Figure 3. Correlation between V_N and B_N for alpha particles as a function of the difference between the field-aligned alpha particle and proton velocity components normalized to the '<observed" wave speed. The sign of the ordinate is + (-) if the alphas are in phase (out of phase) with the protons.

Figure 4 *Top*: Ulysses latitude bins over which average values of the anisotropy factor A^2 were calculated plotted versus heliocentric distance. *Bottom*: Latitude-bin averages of the anisotropy factor AZ calculated from the observed distributions of protons, alphas, and electrons (crosses) and from the slopes of the V_N versus B_N scatter diagrams (triangles) for Alfvénic intervals plotted versus heliocentric distance.

Figure 5. Heliocentric distance dependence of the "discrepancy" between the observed values of the anisotropy factor A^2 and that calculated from proton, alpha, and electron distributions (solid circles) and the additional contribution to A^2 calculated from a simple model of the anisotropy duc to interstellar pickup ions (open circles). The points were calculated over the latitudinal bins displayed in Figure 3.

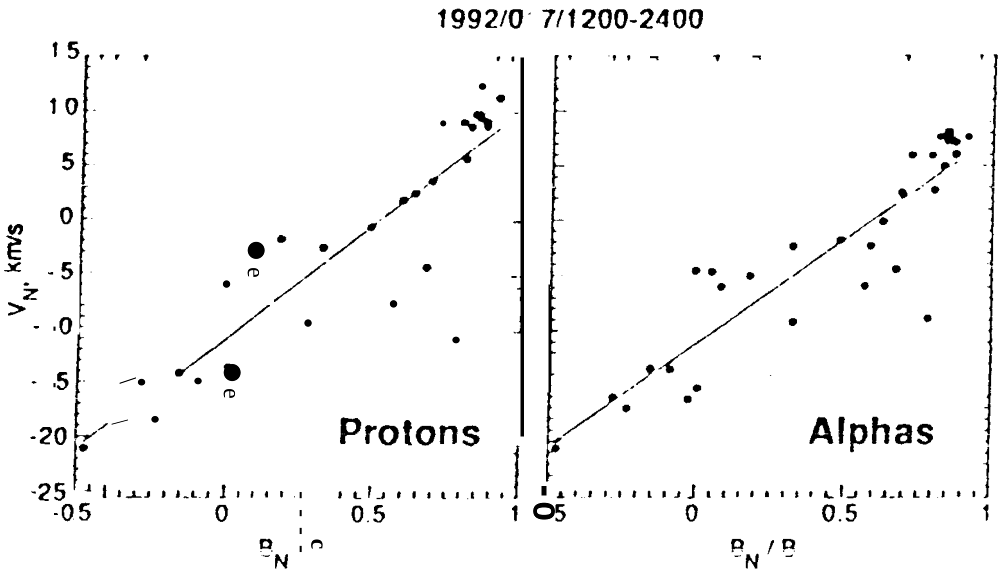


Figure 1

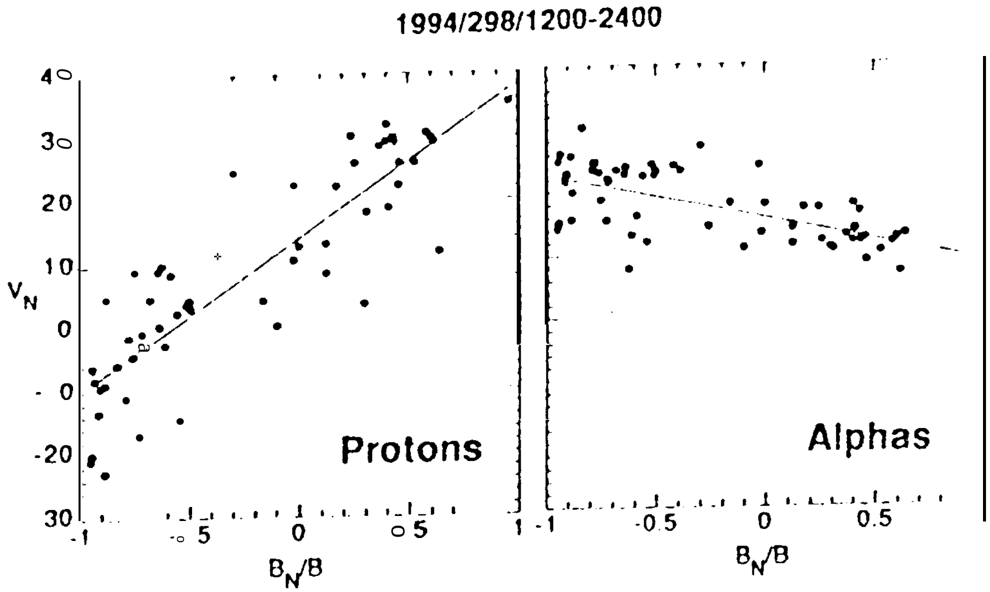

1994/298/1200-2400
V_N
40
30
20
10
0
-20
30
Protons
Alphas
-1
0
1
-0.5
0.5
B_N/B
B_N/B

Figure 2

NONIR and polar data together

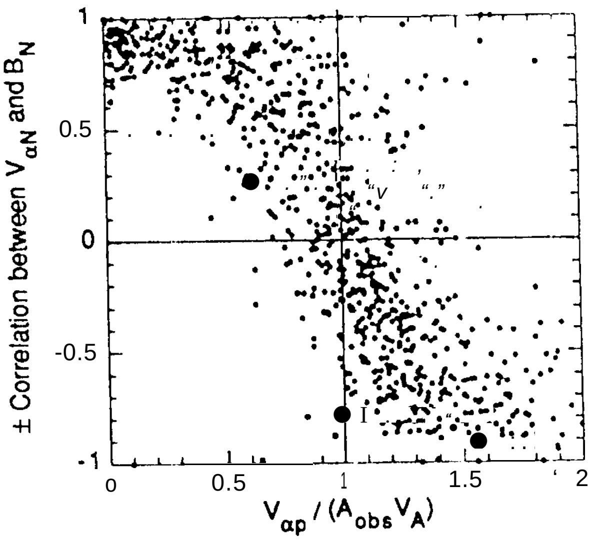
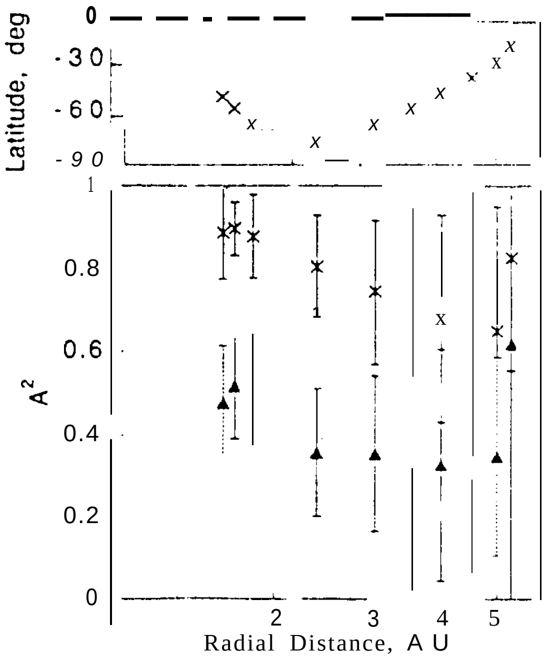


Figure 3

Fig 4

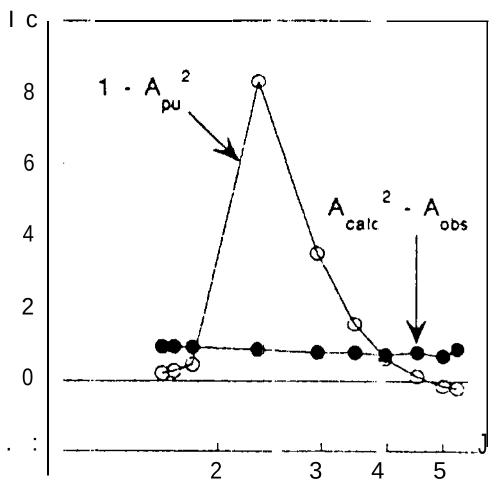


Latitude, deg
0
-30
-60
-90
A²
1
0.8
0.6
0.4
0.2
0
2
3
4
5
Radial Distance, AU

3.5

Fig 5

3"



Radial Distance, AU